arXiv:0704.0358v1 [hep-ph] 3 Apr 2007

Flavor Physics in SUSY at large $\tan\beta$

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We discuss the phenomenological impact of a particularly interesting corner of the MSSM: the large $\tan\beta$ regime. The capabilities of leptonic and hadronic Flavor Violating processes in shedding light on physics beyond the Standard Model are reviewed. Moreover, we show that tests of Lepton Universality in charged current processes can represent an interesting handle to obtain relevant information on New Physics scenarios.

I. INTRODUCTION

Despite the great phenomenological success of the Standard Model (SM), it is natural to consider this theory only as the low-energy limit of a more general model.

The direct exploration of New Physics (NP) particles at the TeV scale will be performed at the upcoming LHC. A complementary strategy in looking for NP is provided by high-precision low-energy experiments where NP could be detected through the virtual effects of NP particles. In particular, flavor-changing neutral-current (FCNC) transitions may exhibit a sensitivity reach even beyond that achievable by the direct searches at the LHC while representing, at the same time, the best (or even the only) tool to extract information about the flavor structures of NP theories.

In view of the above considerations, it is clear that flavor physics provides necessary and complementary information to those obtainable by the LHC.

Besides FCNC decays, also the Lepton Flavor Universality (LFU) tests ($K_{\ell 2}$ and $\pi_{\ell 2}$) offer a unique opportunity to probe the SM and thus, to shed light on NP: the smallness of NP effects is more than compensated by the excellent experimental resolution and the good theoretical control.

II. LFV IN SUSY

The discovery of neutrino masses and oscillations has unambiguously pointed out the existence of the Lepton Flavor Violation (LFV) thus, we expect this phenomenon to occur also in the charged-lepton sector.

Within a SM framework with massive neutrinos, FCNC transitions in the lepton sector like $\ell_i \to \ell_j \gamma$ are strongly suppressed by the GIM mechanism at the level of $\mathcal{B}(\ell_i \to \ell_j \gamma) \sim (m_\nu/m_W)^4 \sim 10^{-50}$ well beyond any realistic experimental resolution [1]. In this sense, the search for FCNC transitions of charged leptons is one of the most promising directions where to look for physics beyond the SM.

Within a SUSY framework, LFV effects originate from any misalignment between fermion and sfermion mass eigenstates. In particular, if the light neutrino masses are obtained via a see-saw mechanism, the radiatively induced LFV entries in the slepton mass matrix $(m^2_{\tilde{L}})_{ij}$ are given by [2]:

$$(m^2_{\tilde{L}})_{i\neq j} \approx -\frac{3m_0^2}{8\pi^2}(Y_\nu Y_\nu^\dagger)_{i\neq j} \ln\left(\frac{M_X}{M_R}\right), \qquad (1)$$

where M_X denote the scale of SUSY-breaking mediation and m_0 the universal supersymmetry breaking scalar mass. Since the see–saw equation [1] allows large $(Y_\nu Y_\nu^\dagger)$ entries, sizable effects can stem from this running [2].

The determination of $(m^2_{\tilde{L}})_{i\neq j}$ would imply a complete knowledge of the neutrino Yukawa matrix $(Y_\nu)_{ij}$, which is not possible even if all the low-energy observables from the neutrino sector were known. As a result, the predictions of leptonic FCNC effects will remain undetermined even in the very optimistic situation where all the relevant NP masses were measured at the LHC.

This is in contrast with the quark sector, where similar RGE contributions are completely determined in terms of quark masses and CKM-matrix elements.

More stable predictions can be obtained embedding the SUSY model within a Grand Unified Theory (GUT) where the see-saw mechanism can naturally arise (such as $SO(10)$). In this case the GUT symmetry allows us to obtain some hints about the unknown neutrino Yukawa matrix Y_ν. Moreover, in GUT scenarios there are other contributions stemming from the quark sector [3]. These effects are completely independent from the structure of Y_ν and can be regarded as new irreducible LFV contributions within SUSY GUTs. For instance, within $SU(5)$, as both Q and e^c are hosted in the **10** representation, the CKM matrix mixing the left handed quarks will give rise to off diagonal entries in the running of the right-handed slepton soft masses [3].

There exist to different classes of LFV contributions to rare decays:

i) Gauge-mediated LFV effects through the exchange of gauginos and sleptons,

ii) Higgs-mediated LFV effects through effective non-holomorphic Yukawa interactions [4].

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[1] The effective light-neutrino mass matrix obtained from a see-saw mechanism is $m_\nu = -Y_\nu \hat{M}_R^{-1} Y_\nu^T \langle H_u\rangle^2$, where $\hat{M}_R$ is the 3×3 right-handed neutrino mass matrix and Y_ν are the 3×3 Yukawa couplings between left- and right-handed neutrinos (the potentially large sources of LFV), and $\langle H_u\rangle$ is the vacuum expectation value of the up-type Higgs.

The above contributions decouple with the heaviest mass in the slepton/gaugino loops m_{SUSY} (case i)) or with the heavy Higgs mass m_H (case ii)).

In principle, m_H and m_{SUSY} refers to different mass scales. Higgs mediated effects start being competitive with the gaugino mediated ones when m_{SUSY} is roughly one order of magnitude heavier then m_H and for $\tan\beta \sim \mathcal{O}(50)$ [5].

While the appearance of LFV transitions would unambiguously signal the presence of NP, the underlying theory generating LFV phenomena will remain undetermined, in general.

A powerful tool to disentangle among NP theories is the study of the correlations of LFV transitions among same families [5, 6, 7].

Interestingly enough, the predictions for the correlations among LFV processes are very different in the gauge- and Higgs-mediated cases [5]. In this way, if several LFV transitions are observed, their correlated analysis could shed light on the underlying mechanism of LFV. In the case of gauge-mediated LFV amplitudes the $\ell_i \to \ell_j \ell_k \ell_k$ decays are dominated by the $\ell_i \to \ell_j \gamma^*$ dipole transition, which leads to the unambiguous prediction:

$$\frac{\mathcal{B}(\ell_i \to \ell_j \ell_k \ell_k)}{\mathcal{B}(\ell_i \to \ell_j \gamma)} \simeq \frac{\alpha_{el}}{3\pi}\left(\log\frac{m^2_{l_i}}{m^2_{l_k}} - 3\right) \tag{2}$$

$$\frac{\mathcal{B}(\mu - e \text{ in Ti})}{\mathcal{B}(\mu \to e\gamma)} \simeq \alpha_{el} \,. \tag{3}$$

If some ratios different from the above were discovered, then this would be clear evidence that some new process is generating the $\ell_i \to \ell_j$ transition, with Higgs mediation being a potential candidate [2].

As regards the Higgs mediated case, $Br(\tau \to l_j\gamma)$ still gets generally the largest contribution among all the possible LFV decay modes [5]. The following approximate relations hold [5]:

$$\frac{Br(\tau \to l_j\gamma)}{Br(\tau \to l_j\eta)} \gtrsim 1\,, \qquad \frac{Br(\tau \to l_j\eta)}{Br(\tau \to l_j\mu\mu)} \gtrsim \frac{36}{3+5\delta_{j\mu}}\,. \tag{4}$$

$$\frac{Br(\tau \to l_j ee)}{Br(\tau \to l_j\mu\mu)} \gtrsim \frac{0.4}{3+5\delta_{j\mu}}\,. \tag{5}$$

$$\frac{Br(\mu \to e\gamma)}{Br(\mu Al \to e Al)} \sim 10\,, \qquad \frac{Br(\mu \to eee)}{Br(\mu \to e\gamma)} \sim \alpha_{el}\,. \tag{6}$$

On the other hand, a correlated study of processes of the same type but relative to different family transitions, like $Br(\mu \to e\gamma)/Br(\tau \to \mu\gamma) \sim [(m^2_{\tilde{L}})_{21}/(m^2_{\tilde{L}})_{32}]^2$, provides important information about the unknown structure of the LFV source, i.e. $(m^2_{\tilde{L}})_{i\neq j}$.

[2] As recently shown in [7], a powerful tool to disentangle between Little Higgs models with T parity (LHT) and SUSY theories is a correlated analysis of LFV processes. In fact, LHT and SUSY theories predict very different correlations among LFV transitions [7].

III. LFU IN SUSY

High precision electroweak tests, such as deviations from the SM expectations of the LFU breaking, represent a powerful tool to probe the SM and, hence, to constrain or obtain indirect hints of new physics beyond it. Kaon and pion physics are obvious grounds where to perform such tests, for instance in the $\pi \to \ell\nu_\ell$ and $K \to \ell\nu_\ell$ decays, where $l = e$ or μ. In particular, the ratios

$$R_P^{\mu/e} = \frac{\mathcal{B}(P \to \mu\nu)}{\mathcal{B}(P \to e\nu)} \tag{7}$$

can be predicted with excellent accuracies in the SM, both for $P = \pi$ (0.02% accuracy [8]) and $P = K$ (0.04% accuracy [8]), allowing for some of the most significant tests of LFU.

As recently pointed out in Ref. [9], large departures from the SM expectations can be generated within a SUSY framework with R-parity only once we assume i) LFV effects, ii) large $\tan\beta$ values.

Denoting by $\Delta r_{NP}^{e-\mu}$ the deviation from $\mu - e$ universality in R_K due to NP, i.e.: $R_K^{\mu/e} = (R_K^{\mu/e})_{SM}\left(1 + \Delta r_K^{e-\mu}\right)$, it turns out that [9]:

$$\Delta r_K^{e-\mu} \simeq \left(\frac{m_K^4}{M_H^4}\right)\left(\frac{m_\tau^2}{m_e^2}\right)|\Delta_R^{31}|^2 \tan^6\!\beta. \tag{8}$$

The deviations from the SM could reach $\sim 1\%$ in the $R_K^{\mu/e}$ case [9] (not far from the present experimental resolution [10]) and $\sim$ few $\times 10^{-4}$ in the $R_\pi^{\mu/e}$ case while maintaining LFV effects in τ decays at the 10^{-10} level. In the pion case the effect is quite below the present experimental resolution [11], but could well be within the reach of the new generation of high-precision $\pi_{\ell 2}$ experiments planned at TRIUMPH and at PSI. Larger violations of LFU are expected in $B \to \ell\nu$ decays, with $\mathcal{O}(10\%)$ deviations from the SM in $R_B^{\mu/\tau}$ and even order-of-magnitude enhancements in $R_B^{e/\tau}$ [12].

IV. FLAVOR PHYSICS AT LARGE $\tan\beta$ AND DARK MATTER

Within the MSSM, the scenario with large $\tan\beta$ and heavy squarks is particularly interesting. On the one hand, values of $\tan\beta \sim 30$–50 can allow the unification of top and bottom Yukawa couplings, as predicted in well-motivated grand-unified models [13]. On the other hand, a Minimal Flavor Violating (MFV) structure [14] with heavy ($\sim TeV$) soft-breaking terms in the quark sector and large $\tan\beta \sim 30 - 50$ values leads to interesting phenomenological virtues [12, 15]: the present

$(g-2)_\mu$ anomaly and the upper bound on the Higgs boson mass can be easily accommodated, while satisfying all the present tight constraints in the electroweak and flavor sectors. Additional low-energy signatures of this scenario could possibly show up in the near future in $\mathcal{B}(B_u \to \tau\nu)$, $\mathcal{B}(B_{s,d} \to \ell^+\ell^-)$ and $\mathcal{B}(B \to X_s\gamma)$. In the following, as discussed in [16], we analyze the above scenario under the additional assumption that the relic density of a Bino-like lightest SUSY particle (LSP) accommodates the observed dark matter distribution

$$0.094 \leq \Omega_{\rm CDM} h^2 \leq 0.129 \quad \text{at } 2\sigma \text{ C.L.}. \qquad (9)$$

In the regime with large $\tan\beta$ and heavy squarks, the relic-density constraints can be easily satisfied mainly in the so called A-funnel region [17] where $M_{\tilde{B}} \approx M_A/2$. The combined constraints from low-energy observables and dark matter in the $\tan\beta$–M_H plane are illustrated in Figure 1 (left). The light-blue areas are excluded since the stau turns out to be the LSP, while the yellow band denotes the allowed region where the stau coannihilation mechanism is also active. The remaining bands correspond to the following constraints/reference-ranges from low-energy observables:

- $B \to X_s\gamma$ $[1.01 < R_{Bs\gamma} < 1.24]$: allowed region between the two blue lines.
- a_μ $[2 < 10^{-9}(a_\mu^{\rm exp} - a_\mu^{\rm SM}) < 4$ [18]]: allowed region between the two purple lines.
- $B \to \mu^+\mu^-$ $[\mathcal{B}^{\rm exp} < 8.0 \times 10^{-8}$ [19]]: allowed region below the dark-green line.
- ΔM_{B_s} $[\Delta M_{B_s} = 17.35 \pm 0.25$ ps^{-1} [20]]: allowed region below the gray line.
- $B \to \tau\nu$ $[0.8 < R_{B\tau\nu} < 0.9]$: allowed region between the two black lines [red (green) area if all the other conditions (but for a_μ) are satisfied].

From Figure 1 (right), we deduce that there is a quite strong correlation between Δa_μ and $\mathcal{B}(B_u \to \tau\nu)$ thanks to the A-funnel region condition $M_H \approx 2M_1$. A SUSY contribution to a_μ of $\mathcal{O}(10^{-9})$ generally implies a sizable effect in $0.7 < \mathcal{B}(B_u \to \tau\nu) < 0.9$. A more precise determination of $\mathcal{B}(B_u \to \tau\nu)$ is therefore a key element to test this scenario.

The interplay of B physics observables, dark-matter constraints, Δa_μ of $O(10^{-9})$, and LFV rates is shown in Figure 2. For a natural choice of $|\delta^{12}_{LL}| = 10^{-4}$ $\mathcal{B}(\mu \to e\gamma)$ is in the 10^{-12} range, i.e. well within the reach of MEG [21] experiment. On the other hand, $\mathcal{B}(\tau \to \mu\gamma)$ lies within the 10^{-9} range for a $|\delta^{23}_{LL}| = 10^{-2}$, that is a natural size expected in many models.

Acknowledgments

I wish to thank the conveners of WG3 for the kind invitation and G. Isidori, F. Mescia and D. Temes for collaborations on which this talk is partly based. I also acknowledge support from the EU contract No. MRTN-CT-2006-035482, "FLAVIANET" and from the Spanish MEC and FEDER FPA2005-01678.

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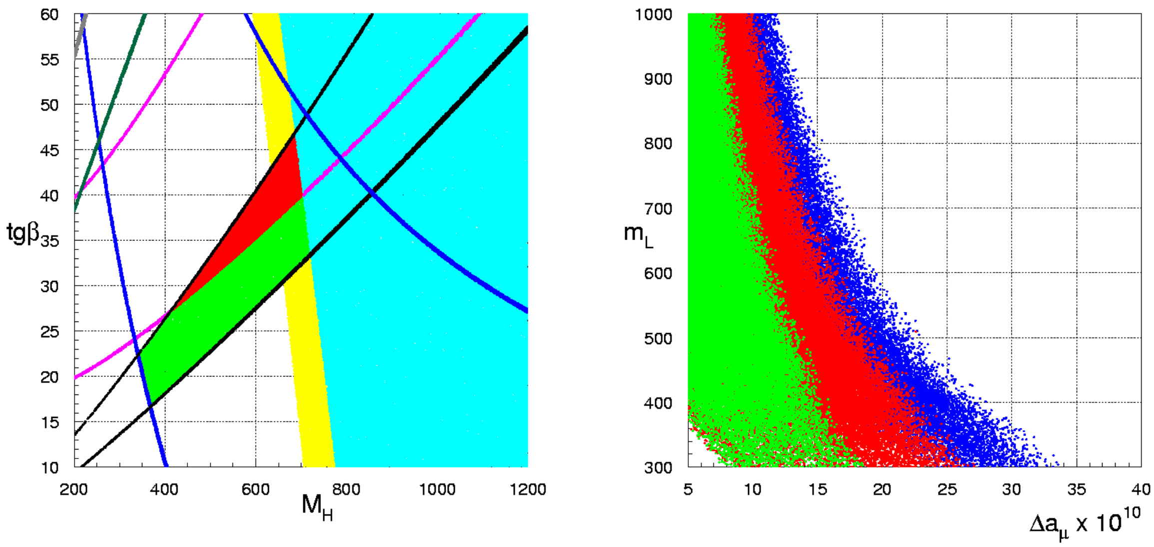

FIG. 1: Left plot: Combined constraints from low-energy observables and dark matter in the $\tan\beta$–M_H plane setting $[\mu, M_{\tilde{\ell}}] = [0.5, 0.4]$ TeV. The light-blue area is excluded by the dark-matter conditions [16]. Within the red (green) area all the reference values of the low-energy observables (but for a_μ) are satisfied. The yellow band denote the area where the stau coannihilation mechanism is active ($1 < M_{\tilde{\tau}_R}/M_{\tilde{B}} < 1.1$); in this area the A-funnel region (where $M_H \approx 2M_1$) and the stau coannihilation region overlap. Right plot: $\Delta a_\mu = (g_\mu - g_\mu^{\rm SM})/2$ vs. the slepton mass within the funnel region taking into account the $B \to X_s\gamma$ constraint and setting $R_{B\tau\nu} > 0.7$ (blue), $R_{B\tau\nu} > 0.8$ (red), $R_{B\tau\nu} > 0.9$ (green) [16]. The supersymmetric parameters have been varied in the following ranges: 200 GeV $\leq M_2 \leq$ 1000 GeV, 500 GeV $\leq \mu \leq$ 1000 GeV, $10 \leq \tan\beta \leq 50$. In both plots, we have set $A_U = -1$ TeV, $M_{\tilde{q}} = 1.5$ TeV, and imposed the GUT relation $M_1 \approx M_2/2 \approx M_3/6$.

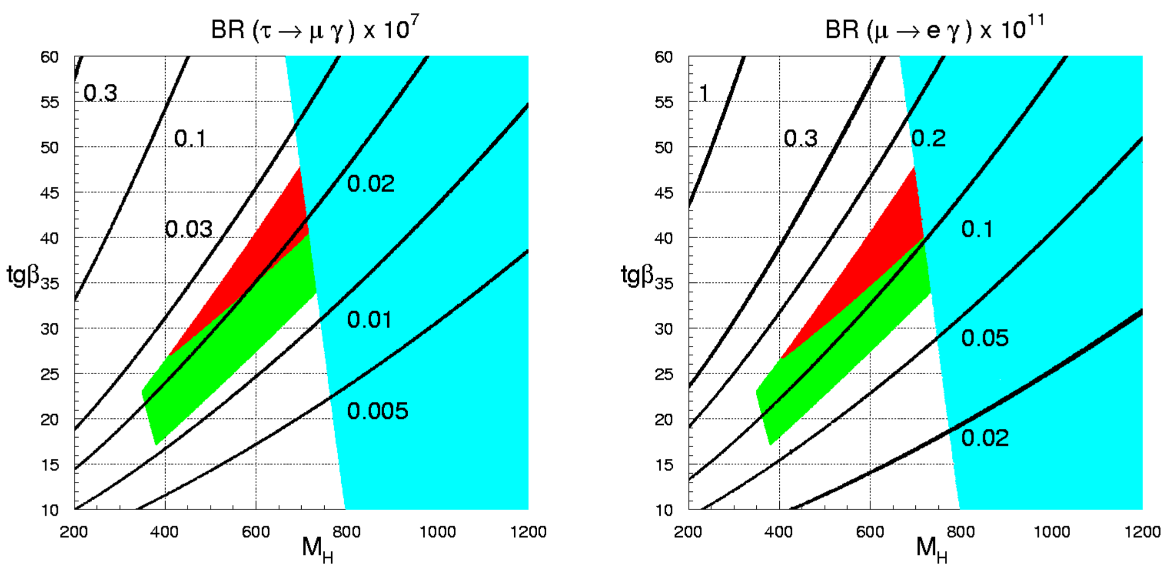

FIG. 2: Isolevel curves for $\mathcal{B}(\mu \to e\gamma)$ and $\mathcal{B}(\tau \to \mu\gamma)$ assuming $|\delta_{LL}^{12}| = 10^{-4}$ and $|\delta_{LL}^{23}| = 10^{-2}$ in the $\tan\beta$–M_H plane [16]. The green/red areas correspond to the allowed regions for the low-energy observables illustrated in Figure 1 for $[\mu, M_{\tilde{\ell}}] = [0.5, 0.4]$ TeV.